CHAPTER 7

LIGHTNING

7-1. Lightning effects on power systems

The frequency of thunderstorms is important in the protection of power systems. The frequency of occurrence of strokes to transmission lines and open country is an indication of the exposure to lightning that an electric power system experiences.

a. An isokeraunic map published by the National Weather Service, which indicates the annual number of thunderstorm days; that is, the number of days on which the weather observer hears thunder or either cloud-to-cloud or cloud-to-ground lightning is useful in planning lightning protection. Using an isokeraunic level of 30 as a reference, an analysis of several thousand measurements made of lightning strokes to transmission lines indicates that a line with a single, 100-foot high ground wire collects 100 strokes per 100 miles per year. A similar line with two overhead ground wires receives more strokes since it collects strokes in a wider swath. The total number of strokes to a line tends to increase with increasing height and decrease with decreasing height.

(1) Knowing the number of strokes to the above transmission lines, we can calculate the number of strokes per unit area (density) by first determining the swath in which a line collects strokes. Again, based on an isokeraunic of 30, the density is 13.7 strokes per square mile per year.

(2) The number of strokes to transmission lines or open ground is assumed to vary directly with isokeraunic. The isokeraunic or storm days do not necessarily reflect the actual number of strokes to earth, however, since a single clap of thunder or a series of thunderstorms lasting several hours would both be counted as one storm day. Thus, the number of strokes to earth can vary widely for a given isokeraunic.

b. In designing lightning protection for power systems, how lightning enters the system, both by direct strokes and by induced surges from nearby strokes; the propagation of surges within the system; and the effects of these surge voltages and currents on the circuits and apparatus within the system must be considered.

(1) Lightning surges entering a power system through direct strokes are the primary concern in planning surge protection. These strokes may hit phase conductors directly, or they may strike the overhead ground wires or masts that shield the conductors. In either case, it is necessary to understand the associated surge currents and voltages produced before a protection system can be designed.

(2) A lightning stroke terminating directly on phase conductors or equipment terminals develops a very high voltage, which, with no surge protection, will flash over the insulation in the majority of cases. If the flashover occurs through air or across porcelain insulation, it rarely causes permanent damage. If, on the other hand, the flashover occurs through solid insulation such as in a transformer or cable, permanent damage results.

c. The magnitude of surge voltages applied to equipment and line insulation systems can be limited by providing grounding masts or ground wires to intercept direct strokes. Even with a shielding network, though, there is some chance of flashover, depending on stroke current magnitude, impedance of the shielding system, and the amount of insulation between the network and the energized circuits.

d. A lightning stroke terminating near a transmission line can induce a voltage in the circuit which seldom exceeds 500 kV. Lines, shielded with overhead ground wires and operating at 69 kV and above, generally have sufficient insulation to prevent flashover by voltages in this range. The same applies to some well insulated 34.5 kV lines. Lower voltage lines, however, with insulation levels appreciably below 500 kV, may be flashed over by induced surges. In most cases, these circuits do not have ground wires, and are, therefore, subject to flashover each time they are contacted by a direct stroke. In general, flashovers by induced surges do not create a significant problem since the number of flashovers from direct strokes far exceeds those from induced strokes.

e. A lightning stroke terminating on a power system initiates traveling waves which propagate within the system. To determine the resulting surge voltages and currents in various parts of the system, a traveling wave analysis is required. Simple networks with linear impedances can be analyzed manually; more complicated networks, characteristic of practical power systems, require analog or digital computer analysis.

(1) First, consider a stroke terminating on the phase conductor of a transmission line. The stroke initiates voltage and current waves traveling at the speed of light in each direction from the terminating point. With a linear impedance, voltage and current have the same waveshape.

(2) The traveling waves are represented by the equation:

$$e = iZ$$

e and i are the voltage and current, respectively, of the traveling wave. Z is the conductor surge impedance.

(3) Surge impedance is circuit impedance as seen by a transient such as lightning. For an open-wire conductor:

$Z = L/C$
L = inductance/unit length
C = shunt capacitance to ground/unit length

(4) A typical surge impedance for a line conductor is 400 ohms. Corresponding values for L and C would be 0.4 H/feet and 2.5 pF/feet, respectively.

(5) Assuming that the stroke current, I, is equal to 2i (that is, the stroke current divides equally at the terminating point), the conductor voltage for a 10,000 A stroke is:

$$e = \frac{IZ}{2}$$

$$= \frac{10{,}000\ \text{A}}{2} \times 400\ \text{ohms}$$

$$= 2{,}000\ \text{kV}$$

Thus, a traveling wave current of 5,000 A (I/2) generates 2,000 kV on the transmission line.

(6) The traveling waves initiated by the stroke continue to propagate along the line until a discontinuity is encountered. At this point, voltage and current waves are reflected back along the line, and at the same time, traveling waves are transmitted beyond the point of discontinuity. Points of discontinuity may be an open circuit breaker, a transformer, another connected line, or a flashover on the line.

(a) To a lightning surge, a transformer appears as a capacitance of 2,000 to 3,0000 power factor, and behaves essentially as an open circuit. As the traveling voltage wave encounters an open circuit, a voltage wave of the same magnitude and polarity as the incoming surge is reflected. The incoming and reflected waves combine, resulting in double the traveling wave voltage (2e) at the open circuit or transformer termination. This is the well known phenomenon of voltage doubling at the end of a line.

(b) For an open circuit termination, the reflected current wave has the same magnitude as, but opposite polarity to, the incoming wave, resulting in zero current at the open end of a line.

(c) Now consider a line terminated in a perfect short circuit. The incoming and reflected voltage waves have the same magnitude and opposite polarity resulting in zero voltage at the terminal. The current waves have equal magnitude and the same polarity, resulting in double the traveling wave current (2I). This is the well known phenomenon of traveling wave current doubling when it encounters a short circuit.

(d) An arrester discharging a current at the end of a line is a close approximation to the short circuit case, since the arrester resistance is very low compared with the line surge impedance. The current which the arrester must discharge, therefore, is nearly double the line traveling wave current. This is an important concept in considering arrester discharge duty from lightning surges.

(7) Another useful concept which can be calculated simply is the determination of the surge voltage in a substation with any number of connected lines.

(a) The substation voltage can be written:

$$E = \frac{2e}{n}$$

e = incoming traveling wave voltage
n = total number of connected lines including that on which the surge originated

Assuming an incoming voltage of one per unit (p.u.),

E = 2, 1, 0.67, and 0.5 p.u. for one, two, three, and four connected lines, respectively

(b) This simple calculation illustrates the advantages of multiple lines in reducing surge voltage in a substation.

(c) As noted previously, typical surge impedance for a phase conductor is 400 ohms. Some other typical values are:

Overhead ground wire – 450 to 500 ohms
Two overhead ground wires (in parallel) – 350 ohms

Steel transmission tower – 200 ohms
Cables – 15 to 40 ohms

(d) The propagation velocity in each of these elements is essentially that of light, with the exception of cables in which propagation velocity is about 50 percent of that of light, depending on the dielectric constant of the insulating material. These values are useful in representing power systems in detailed traveling wave analysis using analog or digital computer methods.

f. In protecting power systems against lightning, surge voltages and currents must be considered. In general, lightning protection is primarily concerned with surge voltages; surge currents cause less concern. A lightning stroke to a power system develops very high surge voltages across equipment and line insulation systems. If these voltages exceed the insulation strength, a flashover occurs. A flashover through air or over porcelain insulation (commonly used for transmission line insulation) does not usually produce permanent damage. In generators, transformers, or motors, however, where solid insulating materials are used, a flashover results in permanent damage.

g. Once lightning enters a power system, the surge current is unlikely to cause any damage. Although the current may be extremely high, it is very short lived and can easily be handled by a small conductor. The largest recorded conductor to be fused or vaporized by a direct stroke was a No. 10 AWG . The size of conductors, installed expressly for conducting lightning currents, is usually determined by mechanical strength considerations, rather than by current-carrying capacity. On some rare occasions overhead ground wires have been severed by lightning at the point of contact. This is probably due to the stroke channel heating the conductor at the point of impingement, rather than from simply conducting the lightning current.

7-2. Principles of protection

It has been shown that a modest lightning stroke of 10,000 A develops a 2,000 kV voltage when it terminates on the phase conductor of a transmission line. Obviously, lines and equipment cannot be insulated to withstand voltages in this range. A more practical alternative is to limit voltages to a much lower level. This involves two basic principles: the use of masts and overhead ground wires to shield equipment and circuits from direct strokes; and the application of arresters to limit surge voltages to levels well below practical equipment insulation levels.

a. Shielding masts are commonly used in substations and overhead ground wires are used in both substations and on transmission lines. Both use the lightning rod principle. The following calculation illustrates how a well-grounded mast limits the surge voltage magnitude.

(1) Consider a mast grounded through a 5 ohm resistance and receiving a 10,000 A stroke.

Voltage developed = 10,000 A x 5ohms
= 50 kV

(2) The voltage at the top of the mast may be somewhat higher since our calculation ignores inductive drop. However, this voltage is significantly less than the 2,000 kV that would be developed for the same stroke on a conductor. Grounded masts and grounded wires, then, offer an important reduction in the magnitude of surge voltages.

b. Even with an effective shielding system, the surge voltages to allow for voltages developed by strokes to the shielding network must be limited to magnitudes consistent with practical and economical equipment insulation levels. On rare occasions strokes may also bypass the shielding system and terminate directly on the energized circuits. For these situations, an arrester is used to control and limit surge voltages to a safe level. The arrester, applied on or near the terminals of the protected equipment, is connected from phase to ground. Under normal operating conditions, the arrester has no effect on the power system. Under surge conditions, the arrester will spark over and conduct the surge current to ground, limiting the voltage applied to the equipment insulation to a safe level. After conducting the surge current to ground, the arrester will interrupt the power-follow current and restore itself to its normal operating conditions.

7-3. Lightning protection systems

Modern offices and other facilities furnished with computer equipment and other sensitive electronic devices demand effective lightning protection to assure reliable operation. Surges in the power system induced by a lightning stroke can cause equipment malfunction or the introduction of false data or commands. Also, lightning-generated electrical energy levels are extremely high and can cause significant damage to electronic components. Such damage can occur when the equipment is turned off, and in some instances, even when it is disconnected from the power receptacle.

a. When lightning strikes a power line, there is a zone extending to each side of the actual stroke where the lightning voltage may greatly exceed the insulation level of the line, and flashover to ground will occur instantaneously. Simultaneously, traveling waves are generated in the conductors on either side of the strike point. These traveling waves have two components: voltage and current. The voltage magnitude is equal to the current magnitude multiplied by the surge impedance of the line and less than the flashover voltage of the system insulation. These surges travel along the overhead line at about 1000 feet per microsecond (the speed of light). Research shows that a lightning stroke produces more energy than has previously been considered possible. A typical lightning stroke carries nearly 3000 million kW at approximately 125 million volts and an average current of over 20,000 A.

(1) A typical lightning surge has an extremely steep wave front, which means that its voltage is rising at the rate of millions of volts per microsecond. The steep wave front is followed by a short wave tall, which means that after crest voltage is reached, surge voltage diminishes to half crest value in about 50 microseconds and completely dissipates in 100 to 200 microseconds.

(2) The development, testing, and correlation of insulation with lightning protective devices has been facilitated by adoption of a standard 1.2 x 50 voltage wave as representative of impulse surges. In the 1.2 x 50 microseconds wave, crest is reached in 1.2 microseconds, and the wave decays to half crest in 50 microseconds.

(3) High-voltage testing laboratories have developed surge generators that can simulate lightning strokes. Not only have the 1.2 x 50 microseconds waves been produced, but the generators can also produce the steeper-front waves with which arresters are tested for front-of-wave sparkover (as specified by standards).

(4) While lightning is usually considered synonymous with extremely high voltage, it is the current component in the lightning stroke that is the measure of its effect on a stricken object. The instant a voltage-sensitive device such as a surge arrester sparks over, it becomes a current-carrying path or relatively low impedance for the duration of the surge discharge. Major segments of the arrester's protective characteristics are determined by its performance in discharging the surge current.

(5) Elaborate scientific investigations have been made to measure and record lightning stroke currents. A wide range has been reported, varying from lows of 1000 A to highs of more than 200,000 A, emphasizing the unpredictability of lightning.

(6) Overvoltage surge protection for power lines and equipment can be devised by using arresters or by a combination of shielding and arresters. Because of the unpredictable nature of the lightning phenomena, engineering analyses are based on statistical data, and reasonable service continuity can usually be assured through correlation of scientific investigations, available weather records, such as isokeraunic maps, and appropriate protective equipment.

b. To provide the most effective safeguard, a lightning-protection system must be appropriate for the type of structure and its construction characteristics. Three protection systems are available and each should be considered:

(1) A conduction system has been in use for many years.

(2) An attraction technique has recently been gaining popularity.

(3) A dissipation system is another new method available.

(4) Other factors that must be considered in providing lightning protection for sensitive equipment include making sure that all parts that carry a lightning electrical discharge are located far away from items being protected. Extensive design data and installation guidelines for lightning-protection systems are provided in National Fire Protection Association (NFPA) 780-1997, "Standard for the Installation of Lightning Protection Systems;" the Underwriters' Laboratories (UL) 96A "Master Label Code;" and the Lightning Protection Institute's (LPI) LPI-175 "Installation Code." Isokeraunic maps also provide essential information on lightning frequencies.

c. The oldest and most commonly used protection method is the conduction system, sometimes termed as the Franklin Rod or Faraday Cage system.

(1) Air terminals (lightning rods) on the structure roof are connected to a grid of interconnecting (coursing) conductors, which connect to down conductors that extend down to earth and connect to appropriate grounding electrodes. The grounding electrodes can be individual ground rods or a conductive ring buried around the building perimeter or both.

(2) All system components are made of copper, anodized aluminum, or stainless steel.

(3) To complete the conventional lightning-protection system installation, all metallic elements (roof fans, vents, etc.), grounded or isolated, which are located on the roof or in the exterior walls near the down conductors, must be bonded to the down conductors because the possibility of a sideflash exists. A sideflash is an arc caused by a difference in potential between a down conductor and a metallic element. The bonding eliminates potential difference and prevents high current flow from damaging these components.

(4) Recent changes in standard guidelines have redefined the outline of the zone protected by any one standard air terminal. Originally, the accepted standard indicated that the area protected was defined by a 60° cone starting at the tip of the air terminal, surrounding the terminal, and extending to earth, without regarding the terminal height. Now, however, research and better data define the protected zone as an area under an arc that has a maximum radius of 150 feet and is tangent to the earth while touching the tip of an air terminal.

(5) This is important for structures exceeding 150 feet in height because additional air terminals must be installed at an appropriate intermediate level, as well as at roof level.

(6) Other protection requirements for high-rise buildings include the electrical interconnection of the steel column components or installation of conductive loops around the building at vertical intervals not exceeding 60 feet. A bonding conductive loop must also be made at ground level and at roof level. Furthermore, all grounded building elements (roof fans, vents, etc.) within 12 feet of the main roof must be connected to the protection system. Also, buildings over 75 feet high must use larger system components per the requirements of the Lightning Protection Code, NFPA 780-1997.

d. The lightning attraction system pulls a lightning stroke to a grounding point located away from the building or the sensitive equipment area. This system uses a spherical/saucer-shaped air terminal (in place of a Franklin lightning rod) and a low-impedance grounding path using components similar to those used with a standard conduction system.

(1) When a storm is in the area, the spherical/saucer terminal generates an ion streamer that attracts and creates a path for a lightning discharge to follow. The strength of the ionized path produced by the attraction device increases as a charged cloud moves closer. The lightning discharge then occurs at the attraction device location rather than at the structure housing sensitive equipment. It is important that the path to ground have the lowest impedance possible so that the high currents involved can be handled safely.

(2) Two terminal designs are in use: one uses radioactive isotopes to initiate the ion streamer; the other has a patented ion-initiator design that does not require the radioactive isotope. Both systems have successful track records proven by hundreds of installations.

(3) This system using the ion-type terminal has been successfully tested in U. S. labs where 95 percent of discharges tested were attracted away from conventional rods by these terminals.

e. The third lightning-protection method used is a dissipation system. These installations rely on many small metallic points to create a massive ionized field that continually discharges the electrical field created by the storm. In the area around the dissipater, the field never reaches the lightning flashover point. Dissipation devices come in a variety of configurations, yet the operating principle is the same. Each point discharges a small amount of the potential difference between the cloud and earth. This action creates a continuous low level current flow, and as a result prevents a lightning strike from occurring. Thousands of these installations have proven to be successful. The committee for NFPA 780 is considering a wording change that will allow dissipation systems to be installed under their standards.

f. To provide effective protection, it is of utmost importance that these three systems have a low-impedance path to ground. This applies to all components and connections from the air terminals to the grounding electrodes. Low impedance is essential so that the huge currents involved will follow the design path in preference to alternative paths offered by building materials such as wood, brick, tile, stone, or concrete. When lightning follows these higher impedance paths, extensive damage may be caused by the heat and mechanical forces generated during the passage of the lightning discharge.

(1) A low-impedance path reduces the potential difference between the storm system, the earth, and the protection to the point where a stroke does not occur or at least is somewhat controlled. Even with installations built on solid rock, an extensive low-impedance ground electrode/system is required, as well as solid connections between components and earth. Standards do not call out a specific ohmic ground value; however, every effort must be made to obtain the lowest value possible.

(2) A number of techniques can be used to lower earth resistance or provide an effective grounding network, as described in NFPA 780. Two additional effective methods for reducing earth resistance are achieved using chemical soil conditioning.

(3) Where the soil is of a high-resistance composition, calcium or sodium chloride has historically been buried with the grounding electrodes to increase conductivity. However, with this technique, the conductor and the salt usually require replacement every few years. To reduce the labor and expense required to make this replacement, a chemically filled rod has been developed.

(4) A second ground conductivity enhancer is a plastic-like material that is poured over the grounding electrode system before it is buried. This enhancement technique reduces the potential difference between the electrical system grounding path, the building structure, and the earth.

g. Interconnecting conductors are as important as other components. Tests in high-voltage laboratories demonstrate that a steep voltage wave front, such as created by lightning, causes the surge impedance in conventional conductors to increase to the point that side-flashes occur. Installation of multiple grounding conductors for buildings and a roof grid system creating a Faraday Cage reduces the magnitude of current flow in any one conductor. However, sideflashes can still occur.

(1) Standard down conductors are usually large bare copper or aluminum stranded conductors that are constructed particularly for the lightning-protection industry. A recent advancement is a coaxial cable that reduces the surge impedance as well as flashover. However, this cable is more costly than other conventional conductors.

(2) The most effective lightning-protection system can be selected after a study of the isokeraunic (lightning frequency for the area), and an evaluation of the structure/site characteristics. Isokeeraunic maps and related data are available from NFPA 780.

(3) A computerized program has been developed that predicts site vulnerability, building area susceptibility, and the magnitude of the possible stroke. Typical inputs to the program are structure height, site height above sea level, storm probability from area records, and the building configuration. From this data, the probability, location, and magnitude of a strike on the building can be determined. The program's accuracy has been as statistically accurate as the input data. Using this approach, the best-suited protection system can be installed, and sensitive equipment can be located away from strike-prone areas.

h. Other methods are used to protect equipment from lightning damage. For example, over transmission lines, substations, or high towers, a protective shielding cable sometimes called a "skywire" is installed. It is a well-grounded bare conductor, usually mounted several feet above the conductors or equipment to be protected. When lightning strikes in the vicinity, induced voltage surges tend to be carried by the shielding skywire instead of the protected conductors or equipment. Lightning arresters and surge protectors are also used to provide protection. These devices, which should be UL listed, prevent lightning induced currents and switching surges from entering the electrical and distribution/voice/data system. These protective devices are connected between the protected system conductor and ground. Normally, they see an abnormally high voltage, such as would be caused by a lightning stroke, their resistance breaks down, carrying any high currents to ground. After the danger is over, normal high resistance is restored.